REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE October 16, 2002	3. REPORT TYPE AND DATES COVERED Final Progress Report

4. TITLE AND SUBTITLE
Polarization & Diffractive Optics for a Snapshot Imaging Spectropolarimeter

5. FUNDING NUMBERS
DAAD19-01-1-0811

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8. PERFORMING ORGANIZATION REPORT NUMBER
318810

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
42812-PH
.1

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

A snapshot imaging channeled spectropolarimeter is under development. This instrument combines channeled spectropolarimetry and computed tomography imaging spectrometry to enable the capture of spatially and spectrally resolved polarization data with no moving parts. Our goals under this contract were the design and acquisition of two high-order retarders and a computer-generated holographic disperser. These have been accomplished.

14. SUBJECT TERMS
Spectometry, polarimetry, spectropolarimetry, imaging

15. NUMBER OF PAGES
13

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

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1 Statement of the problem

Imaging spectrometry and polarimetry are promising techniques for the detection and identification of manmade objects in natural backgrounds. Spectrometry enables detailed comparison of target and background spectra. Polarimetry allows the observer to capitalize on the fact that light emitted from and reflected by smooth surfaces tends to acquire a polarized component.[1] Polarization information then has the potential to highlight manmade objects despite spectral camouflage. We report on development of an imaging instrument which integrates both spectrometry and polarimetry functions. The instrument will be capable of characterizing the state of polarization of radiation from each pixel of a target scene by measuring all four components of the Stokes vector as a function of wavelength.

The data acquired can be interpreted as an image of a four-dimensional volume, since a measure of radiance is obtained for four independent variables or indices: two spatial variables (x, y), wavenumber (σ), and the Stokes vector index (j). It should be noted however that the Stokes vector index has only four possible values (the integers from 0 to 3), whereas the x, y, and σ dimensions will each be segmented into a greater number of intervals. We refer to this four-dimensional volume as the spectropolarimetric hypercube. For example, our goal for a proof-of-principle system is to obtain on the order of 50×50 pixel spatial resolution with 16 wavelength bands in the spectral image for each Stokes component. Figure 1 illustrates the concept of the four-dimensional hypercube.

Conventional spectrometers and polarimeters are generally unable to image all of the dimensions of the hypercube at once. They are inherently sensitive to a one-, two-, or three-dimensional subset of the volume, and must scan out the remaining dimensions in some manner. For example, a camera with a narrow-band filter could be used to obtain a single x,y slice through the hypercube. In this slice x and y vary while σ is fixed at the wavenumber passed by the filter and j is held at zero. The entire four dimensions could be swept out by swapping in filters with different transmission wavelengths and sets of polarizers and retarders, using two independent filter wheels in front of the camera. Similar examples can be made for other systems, such as slit spectrometers and whisk broom scanners (see Figure 2).

Two drawbacks of systems which require scanning are immediately apparent. First, moving parts (such as rotating filter wheels and dithering mirrors) are generally employed, and these are undesirable from the standpoint of reliability. Second, a relatively long time is required for the capture of a complete data set, since multiple exposures are made sequentially in time. Changes in the target scene during scanning manifest themselves as artifacts in the results. Scanning systems thus have limited ability to acquire data on rapidly changing scenes, such as moving targets or targets viewed from moving platforms. A brute force method for avoiding scanning is to use several separate systems viewing the same scene in parallel, possibly with beam splitters to direct light to each. Such systems tend to be expensive, however, since multiple focal plane arrays (FPAs) and a considerable investment in optics are generally involved. Furthermore, registration of the images from the separate systems is problematic.

The system under development promises to circumvent these difficulties via snapshot capability. It will capture data with coverage of the entire hypercube in a single integration time with a single FPA.

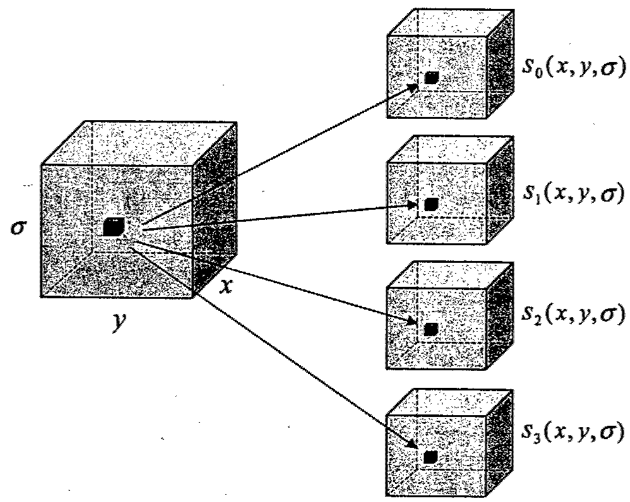

Figure 1: An illustration of the four-dimensional (x, y, σ, j) nature of the data acquired by an imaging spectropolarimeter.

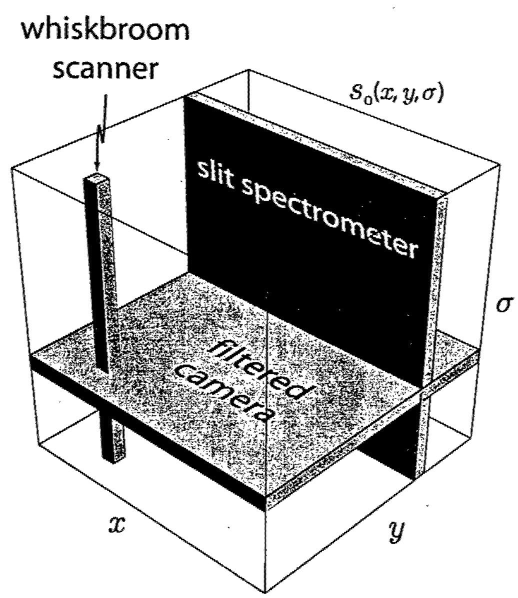

Figure 2: The lower-dimensional volumes which various spectrometer types are capable of imaging without scanning. Such spectrometers could be used with scanning to obtain spectral and spatial data on the s_0 polarization component, with additional measures (such as swapping of polarizers and retarders) necessary to obtain complete polarimetric data.

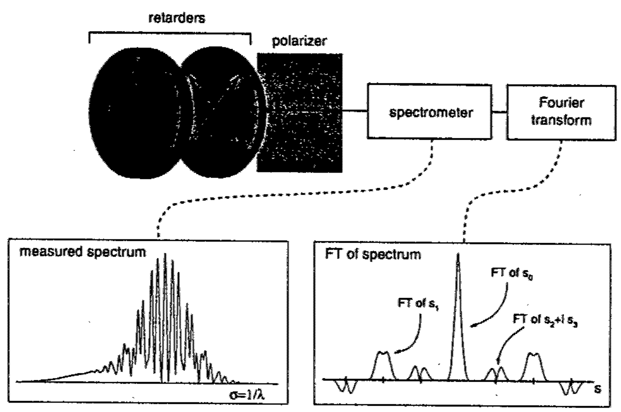

Figure 3: The channeled spectropolarimeter (after Oka and Kato[2]). The complicated spectrum recorded at the output of the polarization optics is formed by a superposition of the Stokes component spectra modulating carriers. With proper choice of carrier frequencies, the Stokes components can be isolated in the Fourier domain.

2 Summary of results

2.1 Channeled spectropolarimetry

The instrument will operate through the fusion of two techniques: channeled spectropolarimetry[2–4] and computed tomography imaging spectrometry.[5] Accordingly, it is referred to hereafter as a computed tomography imaging channeled spectropolarimeter (CTICS). Figure 3 illustrates the principle of operation of a channeled spectropolarimeter. The radiation under analysis is passed through two thick (high order) retarders and a polarizer, and the spectrum of the exiting light is recorded by a spectrometer. The fast axis of the first retarder is aligned with the transmission axis of the polarizer, and the second retarder is oriented with its fast axis at 45° to the polarizer's axis.

The recorded spectrum is a linear superposition of the Stokes component spectra of the incident light, in which the coefficients are sinusoidal terms depending on the retardances of the retarders. Since each retardance is nominally proportional to wavenumber σ, the Stokes component spectra are modulated. With proper choice of modulation frequencies (i.e. proper choice of retarder thicknesses) the Stokes component spectra can be separated in the Fourier domain. This technique is analogous to sideband modulation in radio communications.

The term *channel*, as used in the name given to this technique, occurs as the convergence of two different meanings. In the sideband modulation analogy, individual spectra may be regarded as channels (in analogy to television channels). Dark bands or nulls in an optical spectrum are also termed channels, and a spectrum containing them is sometimes referred to as a channeled spectrum.[6] The carrier waves in the channeled spectropolarimeter result in channeled spectra, as illustrated in Figure 3.

2.2 Computed tomography imaging spectrometry

If used in combination with a snapshot imaging spectrometer, the channeled spectropolarimetry technique acquires snapshot imaging capability. The computed tomography imaging spectrometer

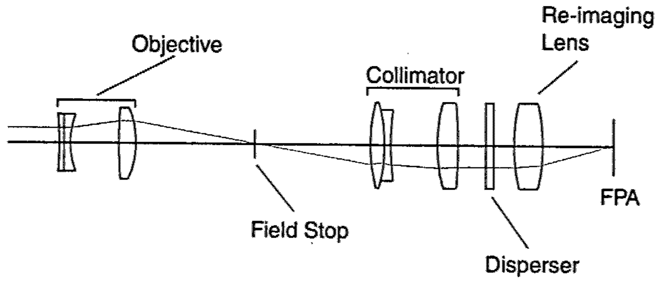

Figure 4: The CTIS Layout. The lens depictions are meant only to be representative of the role each lens plays in the system. Commercial objectives are usually used in the roles of objective, collimator, and re-imaging lens.

(CTIS), developed in large part in our laboratories, is just such a spectrometer. CTIS obtains spatial and spectral data simultaneously by imaging through a computer-generated holographic disperser and carrying out a reconstruction using the mathematics of limited-angle tomography.

The basic layout of the CTIS architecture is shown in Figure 4. The objective lens forms an image of the scene under study in the field stop, which defines the instrument's field of view. The light from this image is then collimated, passed through a computer-generated holographic disperser (CGH) and imaged onto a camera's FPA. The image from each wavelength present in the scene is dispersed into a grid of diffraction orders on the FPA, with the separation between orders increasing with wavelength.

Imaging spectrometers gather data over a three-dimensional (x, y, and λ) volume, sometimes referred to as the data cube. The data cube is a subset of the four-dimensional hypercube discussed earlier. The effect of the dispersion of the CGH can be viewed as generating projections from various angles through the data cube onto the FPA, as illustrated in Figure 5. An estimate of the data cube is reconstructed from these projections by computed tomography. The reconstruction is quite computationally intensive and is carried out on a high-performance computer workstation. The spatial and spectral resolution achieved is constrained in part by the number of pixels in the focal plane array. As one would expect, increasing the number of pixels allows finer sampling of the spatial and spectral content of the image and therefore better spatial and spectral resolution. The complete CTICS system is obtained by combining the channeled spectropolarimeter and CTIS systems, as illustrated in Figure 6.

The main goals of our efforts under this contract have been the design and acquisition of the retarders and CGH disperser for a prototype CTICS system. The prototype is designed for the visible spectrum (0.4–0.7 μm in wavelength). These optical elements have been designed, fabricated, and delivered to us. We describe the designs for the elements in the following sections.

2.3 Retarder design

Assuming each retarder is fashioned from a single crystalline material, cut with its optic axis parallel to the retarder's faces, then each retardance δ_k will follow

$$\delta_k = 2\pi d_k \Delta n_k \sigma. \tag{1}$$

The retarder's thickness is given by d_k and Δn_k is its birefringence (the difference in indices of refraction for its slow and fast axes). It is clear from Equation 1 that the retardance of each retarder

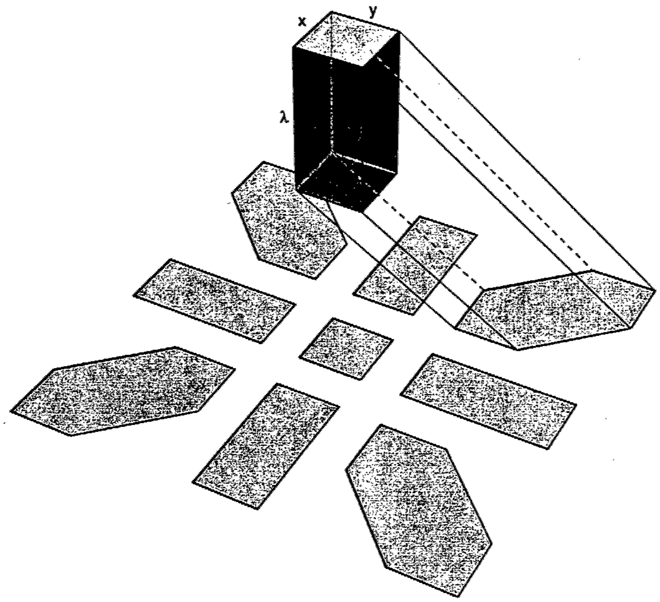

Figure 5: The dispersion of the CGH causes the separation of diffraction orders to increase with wavelength, resulting in several projections of the data cube onto the FPA.

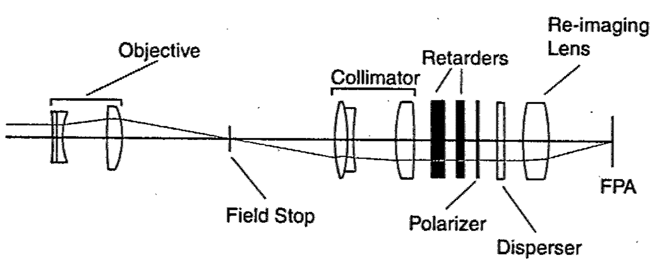

Figure 6: The CTICS Layout. The lens depictions are meant only to be representative of the role each lens plays in the system. Commercial objectives are usually used in the roles of objective, collimator, and re-imaging lens.

will vary nominally in proportion to wavenumber σ. This dependence on wavenumber gives rise to the carrier waves in the sideband modulation analogy via factors of $\cos\delta_k$ and $\sin\delta_k$ which arise in a treatment of the system using the Mueller calculus. (See Sabatke *et al.*[7] for further details.)

The frequency of these sinusoids is set by the product of the retarder's thickness and and birefringence, which may be recognized as the optical path difference (OPD) between the paths of rays polarized respectively along the slow and fast axes of the retarder. In many polarization applications, retarders are made as thin as possible in order to minimize the variation of retardance with wavelength. In the channeled spectropolarimeter, by contrast, the OPDs are deliberately designed with substantial values (which is why the retarders are referred to as *thick*). In real systems, the proportionality between retardance and wavenumber is imperfect because of dispersion in the material from which the retarder is fabricated. That is, the birefringence Δn_k in general depends on σ.

Some care is necessary in using the terminology of spectral analysis, since it can be applied in several ways to the channeled spectropolarimeter. Terms such as *frequency*, *band*, and *band-limited* apply to functions both of wavenumber σ and its conjugate variable under the Fourier transform, which we will denote s. In order to distinguish between the two meanings, we will often prepend σ or s to these terms.

Our system will operate in the visible portion of the spectrum, over a wavelength range of 0.4–0.7 μm or a wavenumber range of 1.4–2.5 μm^{-1}. Our goal is to resolve 16 samples across the spectrum for each Stokes component spectrum. A 25% margin of extra s-bandwidth is designed into the system by using a value of 20 in place of 16. Then the OPD of the first retarder is calculated as

$$d_1 \Delta n_1 \approx \frac{20}{1.1\,\mu\text{m}^{-1}} \approx 18\,\mu\text{m}. \tag{2}$$

In order to obtain equally spaced channels (as illustrated in Figure 3) the retarders should have a 1:2 ratio in OPD. Thus the second retarder should have an OPD of about $36\,\mu$m. Dividing by the birefringence $\Delta n \approx 0.0096$ for quartz yields correspondng thicknesses of 1.9 mm and 3.8 mm respectively.

The tolerances on the thicknesses are fairly relaxed, since we are interested in setting the modulation frequency and not a specific number of waves of retardance. Tolerances of $\pm 0.5\%$ were specified to the vendor. The flatness of the retarder faces was specified at a quarter wave (at a test wavelength of $0.633\,\mu$m). Even with flat retarder faces, it is possible for the thickness of the retarder to vary across its aperture as a result of a wedge angle between the faces. The result of such variation is that the carrier waves consist of a superposition of many sinusoids with slightly different frequencies. With increasing σ these sinusoids get out of phase and begin to interfere destructively, resulting in a reduction of the carrier frequency amplitude.

For back-of-the-envelope purposes, we may assume that the frequencies which result from thickness variations in the retarder are uniformly distributed in a range Δh about a nominal carrier frequency h_{nom}. The carrier wave can then be represented as

$$\int \frac{1}{\Delta h}\,\text{rect}\left(\frac{h - h_{\text{nom}}}{\Delta h}\right) e^{i2\pi h\sigma} \text{d}h = \text{sinc}(\Delta h\,\sigma)\, e^{i2\pi h_{\text{nom}}\sigma}. \tag{3}$$

Thus the carrier takes the form of a sinusoid at the nominal frequency h_{nom} with its amplitude modified by a sinc envelope. As shown in Figure 7, the envelope tends to fall with increasing σ. Then if we dictate that the carrier amplitude must not drop below a specified amount (indicated by the dashed line in the figure), the value of the envelope at the upper wavenumber limit of the system's spectral band will be the key consideration. For example, to just meet a 95% amplitude requirement (that is, to have $\text{sinc}(\Delta h\, 2.5\,\mu\text{m}^{-1}) \approx 0.95$), a value of $\Delta h \approx 0.070\,\mu$m is required. This corresponds to a variation of $7.3\,\mu$m in thickness across the retarder's face. For a 1 inch diameter

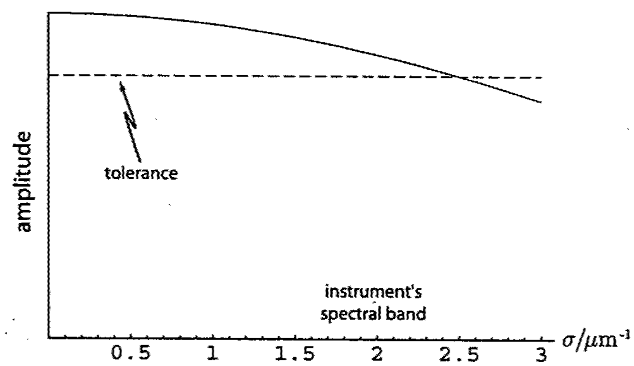

Figure 7: Variations in retarder thickness result in a roll-off of carrier amplitude across the spectrum.

element, we arrive at a wedge tolerance of 60 seconds of arc. A margin of safety was allowed by specifying a tolerance of 15 seconds of arc to the vendor.* The retarders were specified with 1 inch diameter and a broad band anti-reflection coating on each face.

2.4 CTIS design

The resolution required of the spectrometer is related to the desired resolution of the Stokes component spectra by a factor of seven. Since our goal is 20 bands in the final data, we require 140 resolution bands in the CTIS, giving

$$\delta\sigma_{\mathrm{CTIS}} \approx \frac{1.1\,\mu\mathrm{m}^{-1}}{140} \approx 7.9 \times 10^{-3}\,\mu\mathrm{m}^{-1}. \tag{4}$$

The resolution of the CTIS is a complicated topic. The tomographic imaging method, calibration techniques, and iterative reconstruction techniques are all likely to impact its resolution. In practice, values for the spectral resolution of CTIS instruments are usually taken from the number of different wavelengths at which the system is calibrated. Because CTIS is a grating spectrometer, any attempt to characterize its spectral resolution as a single value should probably be made in terms of wavelength rather than wavenumber. Wavelength resolution $\delta\lambda$ and wavenumber resolution $\delta\sigma$ are related (assuming both to be positive) by

$$\delta\lambda = \frac{\delta\sigma}{\sigma^2}. \tag{5}$$

Assuming the CTIS wavelength resolution to be constant across the spectrum, its required value can be conservatively estimated by using the largest value acquired by the wavenumber in Equation 5. This yields $\delta\lambda \approx 1.3\,\mathrm{nm}$, which corresponds to about 240 resolution bands in the CTIS. With this arrangement, the CTIS meets the wavenumber resolution requirement at the blue end of the spectrum and exceeds it (that is $\delta\sigma$ is smaller than necessary) toward the red.

In order to achieve 240 bands of resolution, the highest diffraction order in the CTIS (with a white input) should span at least as many pixels on the FPA. Table 1 gives the prescription for a CTIS

*The thick retarders were fabricated by Boston Piezo-Optics Inc. 38B Maple Street, Bellingham MA 02019. Telephone: (508)966-4988. http://www.bostonpiezooptics.com/.

system we have designed which meets this requirement. The prescription features a 2048×2048 pixel FPA (as shown in the left column of the table), collimating and reimaging optics with respective focal lengths of 300 mm and 60 mm, a 2 mm square field stop, and a period in the CGH of 16 μm (as shown in the right column). The system is intended to make use of a 5×5 array of diffraction orders (including the 0, ±1, and ±2 orders). The figure in Table 1 shows the footprint of the field stop after diffraction for each of the orders. The highest order is diffracted across more than 300 pixels, which meets our goal for spectral resolution. The direct (zero order) image of the field stop measures on the order of 50 pixels on a side. Hence we anticipate approximately 50×50 elements of spatial resolution and 16 elements of spectral resolution in each of the four Stokes components in the final CTICS system.

The CTIS prescription in Table 1 specifies the required period of the CGH. There is however considerable additional effort required to design a suitable CGH.[8] The CGH designer's task is to tailor the diffraction efficiencies of the orders so they increase modestly with order number in those orders used by the system (in this case the 0, ±1, and ±2 orders in both FPA dimensions), fall off sharply at higher order numbers to avoid sending light into unused orders, and remain well-behaved across a broad wavelength band. A phase-only hologram is used to preserve throughput.

The hologram is formed by etching a prescribed surface relief pattern into the face of a transparent substrate. The pattern is periodic, and is formed by replicating a smaller pattern (the unit cell) over the grating's face. The surface relief of the unit cell is described on a rectangular grid, with surface height taken to be constant within each grid element. Each element of the unit cell is termed a phase element (or *phasel*). For this instrument, the CGH unit cell was chosen to consist of an 8×8 array of phasels. Table 2 shows design data and the surface relief of the disperser designed for the spectropolarimeter. It was fabricated[†] in PMMA using an electron beam etch.

2.5 Ongoing work

The specific goals of this contract, designing and acquiring the retarders and disperser, have been accomplished. Our development work is proceeding on several other fronts. These include assembly and interfacing of the spectropolarimeter, and use of a non-imaging channeled spectropolarimeter as a test-bed to study reconstruction and calibration methods. A reference spectrometer featuring a rotating compensator and fixed linear analyzer is under construction.

3 Listing of publications and technical reports

A paper related to this work has been presented and is to be published in proceedings:

D. S. Sabatke, A. M. Locke, E. L. Dereniak, J. P. Garcia, C. P. Tebow, and D. Sass, "Design and development of a snapshot imaging spectropolarimeter," *Thirteenth Annual Ground Target Modeling and Validation Conference*, 5–8 August 2002 (Houghton, MI).

[†]The disperser was fabricated by Dan Wilson of the Jet Propulsion Laboratory, Pasadena, CA.